JOURNAL OF THERMOPHYSICS AND HEAT TRANSFER
Vol. 9, No. 4, October–December 1995

Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Flow of Nitrogen and Superheated Steam Through Cement Mortar

Michael McVay*
University of Florida, Gainesville, Florida 32611
and
Jeff Rish III†
U.S. Air Force Civil Engineering Support Agency, Tyndall Air Force Base, Florida 32403

Introduction

THERE are many areas that are concerned with the flow of gas (air or steam) through portland cement, e.g., nuclear reactor containment, structural fires, and jet exhaust impinging on pavements. To model both the mass and heat migration through cement, coupled partial differential equations concerning the conservation of mass, momentum, and energy must be solved. In the case of the momentum of the fluid, Darcy's[1] expression is used, whereas for gas, Darcy or Klinkenberg's[2] equation is employed. The former is linear with pressure gradient and the latter is nonlinear.

This work concerns quantifying the error of Darcy's expression over Klinkenberg's equation for gas flow in cement under elevated temperatures. The effort involved 18 isothermal steady-state flow tests with pressures varying from 5 to 20 atm for which flow and pressure across the specimens were monitored. Both superheated steam and nitrogen gas were employed. Dry nitrogen was used instead of compressed air because of the adverse effect of the latter. It was found that Klinkenberg's expression was capable of predicting all the flow and pressure results within a few percent, whereas Darcy's expression was in error by 15–25% for both pressure and flow results.

Test Equipment

Figure 1 presents the one-dimensional sample and container for the gas flow experiments. A specimen diameter of 127 mm was employed to diminish edge effects, as well as increase the mass flow rate. To reduce the time to reach steady-state flow and isothermal conditions, the sample thickness was limited to 51 mm. Initially, the testing apparatus had a 25-mm-thick epoxy ring cast around the specimen and sealed at the ends with metal platens. However, under elevated temperatures (200°C and above) the adhesive bond between the epoxy and the cement failed due to dissimilar expansion of the epoxy and cement. Subsequently, it was found that a steel pipe (coefficient of expansion similar to the cement) with a 3-mm gap between its inside wall and the specimen, filled with a high-temperature epoxy, prevented leakage, i.e., the epoxy under elevated temperatures swelled within the gap and formed a tight seal.

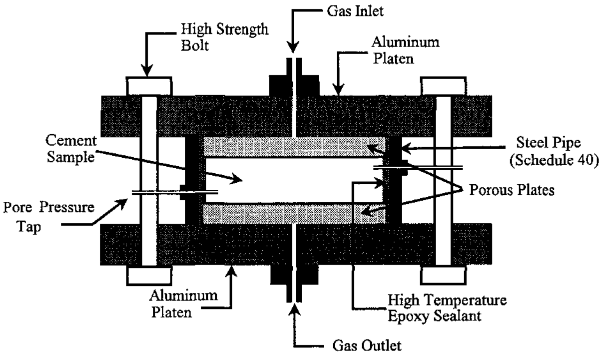

Fig. 1 Sample apparatus for nitrogen and superheated steam testing.

The ends of the steel pipe were sealed to two 305-mm-diam by 26-mm-thick aluminum plates. This was accomplished by cutting a 6-mm groove into each plate, filling them with a high-temperature graphite sealant, and squeezing the steel pipe into the grooves with five high-strength bolts running from plate to plate. The large size of the two end plates was selected to provide a large heat source to convert the saturated steam coming from the boiler into a superheated state, as well as maintain an isothermal state in the specimen.

Supporting the specimen within the test apparatus was a porous aluminum plate. Early attempts to use a ring resulted in fracture of the specimen. Placed on top of the specimen was another porous aluminum plate that was used to ensure that the steam entering the specimen was superheated. Also shown in Fig. 1 are two of four pressure taps (the other two are perpendicular to the view) to measure gas pressures within the pores. The four taps were equally spaced along the sample. The taps were placed by drilling a 4-mm by 13-mm hole into the specimen, filling it with high-temperature epoxy, letting it cure, and then drilling a new 2-mm by 15-mm hole in the epoxy. This approach was employed to measure pore pressure away from the boundary.

Dry nitrogen was provided to the specimen from a high-pressure (135 atm) source stepped down through a regulator to the prescribed upstream pressure. The volumetric gas flow rate was measured by timing the volume of water displaced from a filled burette turned upside down in a pan of water. Care was taken to ensure that water levels inside and outside the burette were the same (i.e., at atmospheric pressure) at the time of the reading.

The steam was provided by a 5×10^3 cm^3 boiler that was thermally regulated with electric coils as shown in Fig. 2. The steam flowed a short distance (0.6 m) in a steel pipe (diameter = 12.5 mm) wrapped with ceramic insulation (o.d. = 155 mm) to the oven holding the specimen. The oven was maintained 10–15°C hotter than the boiler to superheat the steam. The latter was accomplished with the aluminum end platen and porous plate above the specimen (see Fig. 1), as well as the steel pipe carrying the steam into the oven. Thermocouples attached to both end platens (sealed from the oven air), as well as the steel containment pipe, continuously monitored the sample temperature. In addition, the steam temperature

---

Received July 26, 1993; revision received Dec. 26, 1994; accepted for publication Jan. 27, 1995.

*Associate Professor of Civil Engineering, 345 Weil Hall.

†Research Civil Engineer, Headquarters.

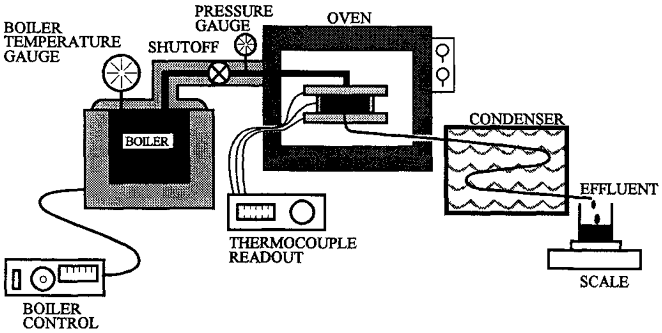

Fig. 2 Equipment used in superheated steam testing.

within the boiler was monitored, as well as the upstream pressure of steam just prior to its entering the oven. The steam exiting the sample and oven was carried by a 6-mm-diam pipe through a condenser, and finally into a glass beaker where it was weighed with time. Figure 2 illustrates the complete setup: boiler, oven, sample apparatus, water condenser, and weight system.

Sample Preparation

To obtain repeatable results, as well as remove the influence of aggregate type and size, the tests were performed on cement mortar. The proportions by weight of the mortar sample ingredients were 1 part type I portland cement, 2.75 parts silica sand, and 0.5 parts water based on ASTM specifications C-109. The silica sand met specification ASTM C-778 for gradation, had a specific gravity of 2.63, and a water absorption of 0.21%. The mortar was cast in steel circular molds and consolidated through vibration. The specimens were allowed to hydrate (cure) for two days in the molds, then removed and submerged for seven days under water. The samples were then dried of surface moisture, weighed, and stored in a moist room for 30 days.

Prior to testing, the specimens had all their free moisture removed. This was accomplished in an oven by increasing the specimens' temperature from 100 to 225°C over a two-week period and monitoring weight loss. To keep moisture out, the specimens were stored in airtight polyethylene bags with desiccant until testing. Based on the water loss, the specimens had a porosity (volume of voids/total volume) of 17.5%.

Experimental Results

Given in Table 1 are the volume flow rates, upstream pressure, and standard deviation for nitrogen flow tests on 10 different samples. It should be noted that the pore space in the mortar had to be free of liquid water or the nitrogen flow was unduly affected. For instance, testing a specimen with 10% of the pore space occupied by water resulted in a sevenfold decrease in its volume flow rate. The latter would not occur for the superheated steam experiments since any liquid pore moisture was evaporated and driven off prior to testing.

Superheated steam flow tests were performed on eight different specimens (two repetitions on each). Presented in Table 2 is the boiler temperature, upstream pressure (absolute), specimen temperature, measured mass flow rates, and standard deviations for all the tests. Each sample was used only once, i.e., after each test, the sample was thrown away.

The Darcy expression for volume flux q (i.e., volume/unit area/unit time) without gravity effects (negligible for present study) is

$$q = -(K/\mu)\nabla P \tag{1}$$

where ∇P is the pressure gradient, μ is the viscosity of the gas, and K is the intrinsic permeability L^2 or constant of proportionality. Klinkenberg's[2] equation is

$$q = K_g \nabla P = (K_l/\mu)[1 + (b/P_{\text{avg}})]\nabla P \tag{2}$$

where K_g is the intrinsic permeability of the material to gas, K_l is the intrinsic permeability of the material to a liquid, and b is referred to as Klinkenberg's equation. From the conservation of mass for one-dimensional isothermal and steady-state flow, K_g may be determined[3]

$$K_g = K_l\left(1 + \frac{b}{P_{\text{avg}}}\right) = K_l\left(1 + \frac{2b}{P_h + P_l}\right) = \frac{2Q_m \mu L P_0}{A(P_h^2 - P_l^2)\rho_0} \tag{3}$$

where P_0 and ρ_0 are atmospheric pressure and density of the gas at the temperature of specimen, Q_m is the mass flow rate, A is the cross-sectional area of the sample, $P_{\text{avg}} = (P_h + P_l)/2$, where P_h and P_l are the high- and low-pressure boundary conditions, respectively.

Using the nitrogen volume flow rate data given in Table 1 along with viscosity μ of 1.78×10^{-2} cP, L of 50.8 mm, ρ_0 of 1.18×10^{-3} gm/cm^3, A of 126 cm^2, P_0 of 1 atm, the K_g in Eq. (3) was found and plotted (Fig. 3a) vs the reciprocal of the mean pressure $[(P_h + P_l)/2]$. From Eq. (3), the intercept of the plot is K_l and its slope is $K_l b$, where K_l is the material's intrinsic permeability to liquid, and b is Klinkenberg's constant. The value of K_l was determined to be 8.038×10^{-17} (m^2), and b was found to be 0.81 (dimensionless) with an $R^2 = 0.999$. Note there is a 25% difference between the intrinsic gas permeability K_g from the low-pressure to high-pressure tests, suggesting that Eq. (2) be used instead of Eq. (1).

The superheated steam data given in Table 2 along with the gas viscosity μ and density ρ_0 as a function of specimen temperature was used to determine the mortar's intrinsic gas

Table 1 Nitrogen testing volume flow rate vs upstream pressure

Upstream pressure, atm	Volume flow rate, ml/s	Standard deviation, ml/s
1.00	0.00	0.00
4.40	1.36	0.07
7.80	4.01	0.12
11.20	8.00	0.19
14.61	13.33	0.27
18.01	20.00	0.42
21.41	27.90	0.51

Table 2 Superheated steam testing temperatures, and mass flow rate vs upstream pressure

Boiler temperature, °C	Upstream pressure, atm	Specimen temperature, °C	Mass flow rate, g/min	Standard deviation, g/min
170.0	7.80	181.7	0.133	0.008
197.6	14.61	207.2	0.39	0.014
207.8	18.01	215.6	0.568	0.023
216.6	21.41	225.1	0.765	0.031

Table 3 Properties of superheated steam and intrinsic permeability of concrete mortar

Specimen temperature, °C	ρ_0, g/cm^3	$\bar{\mu}$, cP	K_g, m^2
181.7	4.82×10^{-4}	1.54×10^{-2}	9.44×10^{-17}
207.2	4.56×10^{-4}	1.61×10^{-2}	8.786×10^{-17}
215.6	4.51×10^{-4}	1.65×10^{-2}	8.687×10^{-17}
225.1	4.43×10^{-4}	1.71×10^{-2}	8.608×10^{-17}

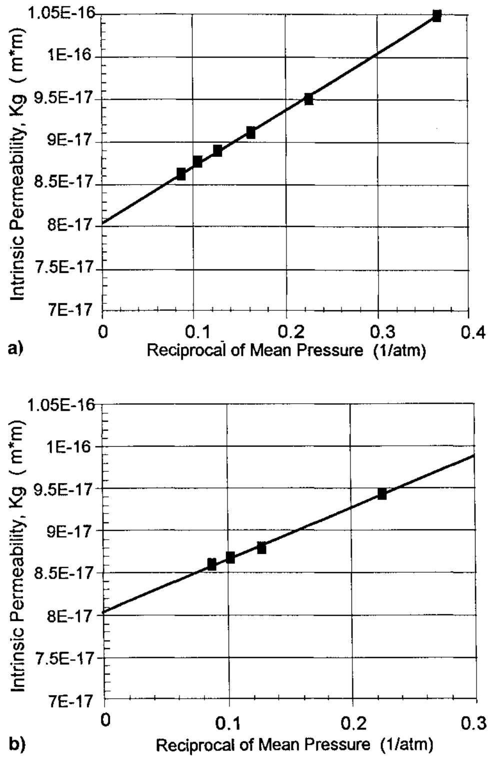

Fig. 3 **Intrinsic gas permeability K_g vs reciprocal of mean pressure: a) nitrogen tests and b) superheated steam tests.**

permeability K_g (Table 3) from Eq. (3), and plotted (Fig. 3b) vs the reciprocal of the mean pressure $[(P_h + P_l)/2]$. The samples' length L was 50.8 mm, and their cross-sectional area A was 126 cm^2. From the plotted data, the value of K_l (intercept) was determined to be 8.04×10^{-17}, and Klinkenberg constant b (slope/K_l) was found to be 0.77 with an $R^2 = 0.99$. Note the value of K_g varied by 20% over the pressure ranges tested, suggesting that a constant K as in Darcy's expression [Eq. (1)] is inappropriate. Also, note that the difference in K_l for both nitrogen and superheated steam data differed by less than 1%, and the b value for both gases differed by only 4%.

Presented in Fig. 4 is the pressure distribution measured across a sample in a nitrogen test with a feed pressure of 10 atm. Evident from the figure, the pressure drop across the specimen is not linear. An analytical expression may be derived by substituting the volume flow rate equation [Eq. (2)] into the conservation of mass expression and solving for pressure. For one-dimensional steady-state conditions, the resulting pressure P is

$$(P + b)^2 = [(P_l + b)^2 - (P_h + b)^2](x/L) + (P_h + b)^2 \tag{4}$$

where x is the distance from the high-pressure boundary, b is Klinkenberg's constant, and P_h and P_l are the high and low pressure at the boundaries, respectively. Plotted as a solid line in Fig. 4 is the solution of Eq. (4) with a Klinkenberg's coefficient b of 0.81. There is less than a 4% error between the measured and predicted pressures across the whole sample. For a b value of 0.0 (Darcy's expression), Eq. (4) was found to be in error by 15% when compared to the measured pressure.

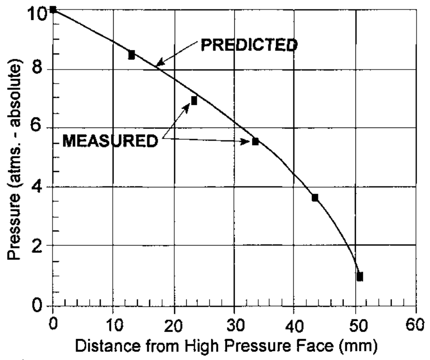

Fig. 4 **Pressure profile across the specimen.**

References

[1] Darcy, H., "Les Fontaines Publiques de la Ville de Dijon," *Dalmont*, Paris, France, 1856.

[2] Klinkenberg, L. J., "The Permeability of Porous Media to Liquids and Gases," *American Petroleum Institute Drilling Production and Practices*, American Petroleum Inst., Washington, DC, 1941, pp. 200–213.

[3] Bear, J., *Dynamics of Fluids in Porous Media*, Elsevier, New York, 1972.

Natural Convection in Horizontal-Layered Porous Annuli

C. P. Pan* and F. C. Lai†

University of Oklahoma, Norman, Oklahoma 73019

Introduction

OVER the past decades, heat transfer in saturated porous media has received considerable attention for its important applications in geophysics and energy-related engineering problems. However, previous efforts have been centered primarily on a homogeneous system, whereas a layered system, although encountered more frequently in engineering practice, has received very little attention. Most available results on heat transfer in layered porous media are limited to simple geometries like horizontal layers[1–4] or vertical layers.[5,6] In addition, their emphasis has been placed on the establishment of the criterion for the onset of convection. For a layered annulus, the results are very few and they are reported only by Muralidhar et al.[7] However, their results show

---

Received May 20, 1994; presented as Paper 95-0417 at the AIAA 33rd Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 10–13, 1995; revision received March 13, 1995; accepted for publication March 13, 1995.

*Graduate Research Assistant, School of Aerospace and Mechanical Engineering. Member AIAA.

†Assistant Professor, School of Aerospace and Mechanical Engineering. Member AIAA.